K9 Operation in May ’00 Dual-Rover Field Experiment

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Abstract

This paper describes the K9 rover operations at the Jet Propulsion Laboratory (JPL) during a dual-rover field experiment involving the NASA Ames Research Center’s K9 rover and JPL’s FIDO rover in May of 2000. We will describe the use of various ground tools used for sequence generation and the onboard conditional executive.

1 Introduction

In this paper, we describe our operations during a dual-rover field experiment conducted by NASA Ames Research Center (ARC) and the Jet Propulsion Laboratory (JPL) from May 14 to May 16, 2000. This was the first use of the K9 rover in field operations. The field experiment took place in Lunar Lake, NV, a remote site near Tonapah, NV, chosen for its Mars-like geology. The operations center was at JPL in Pasadena, CA. The team of planetary geologists at JPL was unaware of the field site location. Given only simulated descent imagery of the site and data obtained during the experiment by the two rovers, the science team was tasked with characterizing the site.

Figure 1: K9 and FIDO in the field.

The experiment was supported in the field by a diverse team consisting of field scientists who documented the experiment from the field perspective and provided “ground truth” for post-hoc analysis, and rover engineers who deployed the rovers each day, ensured rover safety, and handled mechanical and software problems as they arose.

JPL’s FIDO rover and ARC’s K9 rover (see Fig. 1) were used to simulate how two rovers could work together on Mars to do an efficient job identifying, mapping, and sampling specific rocks and soils. FIDO performed the role of a sampling rover, conducting imaging, IR spectroscopy, drilling, and microscopic imaging. K9 performed the role of a scout rover, exploring ahead to find rocks that would be suitable for sampling with the FIDO Mini-Corer. This paper focuses on the operations of the K9 rover during the field experiment. Descriptions of the FIDO and science operations can be found in [1, 2].

2 The K9 Rover

The K9 Rover is a 6-wheel steer, 6-wheel drive rocker-bogey chassis outfitted with electronics and instruments appropriate for supporting research relevant to remote science exploration. The main CPU is a 166 MHz PC104+ mobile Pentium MMX single board computer running the Linux operating system. An auxiliary microprocessor communicates with the main CPU over a serial port and controls power switching and other I/O processing. The motion/navigation system consists of motor controllers for the wheels and pan/tilt unit, a compass, and an inertial measurement unit, which communicate with the main CPU over serial ports.

The camera system consists of a mast-mounted stereo pair of high-resolution SCSI filter-wheel cameras, and three multiplexed stereo pairs of low-resolution RS-170 cameras. One RS-170 stereo pair is mounted on the pan/tilt unit and acts as a navigational camera unit. The other two pairs act as front and rear hazard avoidance cameras and are mounted low on the rover body. The camera multiplexing system has the capability to support up to five additional RS-170 stereo pairs.

During the field experiment, we supported the testing of two experimental instruments from the Mars Instrument Development Program on-board the K9 rover: the Laser Induced Breakdown Spectrometer from Los Alamos National Laboratory, and the flight panoramic camera from Ball Aerospace. Both of these instruments were tested in the field prior to the dual-rover portion of the experiment.

3 K9 Operations

K9 rover operations conducted at JPL were broken up into units called “sols”. Each sol contained one uplink of commands to the rover and one downlink of data from the rover. Preparation for and execution of a sol consisted of six phases: 3D model building from the data obtained in the previous sol, science analysis and planning in a VR environment, command plan generation, plan uplink, plan execution, and data downlink.

3.1 3D Model Building

As the last task of each sequence, K9 obtained monochromatic, panoramic, stereo imagery, which was used to plan the next sequence. A computer vision system, the “Ames stereo-pipeline”, processed these images to efficiently generate accurate high-resolution 3D terrain models of the remote site using binocular disparity information. The models were automatically generated by the stereo-pipeline as image data was received via the downlink process.

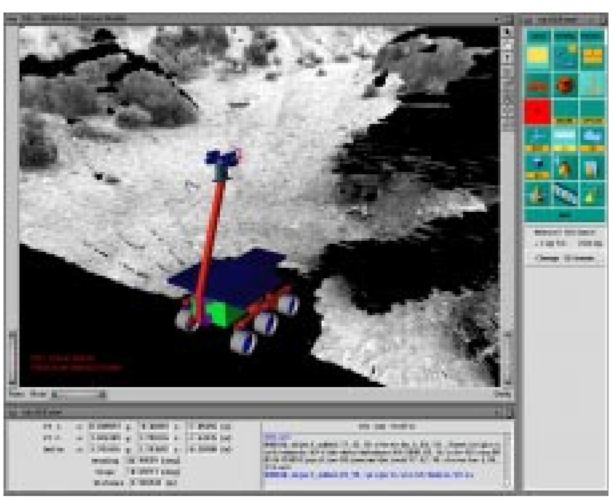

Figure 2: Navigational panorama from Sequence 1 viewed within Viz.

3.2 Virtual Reality Environment for Science Analysis and Planning

The terrain model is viewed and manipulated in a virtual reality system called “Viz” [4]. The objective of Viz is to provide science analysis and operations tools in a high-fidelity 3D environment (see Fig. 2). A suite of measurement tools is provided that allows intuitive interrogation of the remote site, and Viz is integrated with a kinematic simulation engine, called “VirtualRobot”, that provides rover pose and viewpoint simulation capabilities for operations planning.

Using Viz and the low-resolution terrain model from the previous sol, the science team determined the next target rock for investigation and a possible target for a later sequence by evaluating rock size and shape to find suitable targets for FIDO’s Mini-Corer. The science team’s representative conveyed the science goals for the sol to the K9 operations team: the primary target, what type of additional information about the primary target was required by the science team, and the location of the secondary target where the rover would head on the next sequence after obtaining data from the primary target. This second “look-ahead” target gave the rover operations team an idea of a how to orient the rover at the end of the current sequence to facilitate future drive sequences. Since turning is the most inaccurate of the rover’s actions, this strategy of turning and then taking localization imagery enabled the ops team to evaluate the accuracy of the turn in the final navigational panorama of the sequence.

To achieve the science goals, the rover ops team used Viz and the VirtualRobot to plan panorama extents, turn

Figure 3: The Virtual Dashboard.

angles, and drive distances for the sequence. For example, to determine how to image a rock target, the virtual rover can be driven to the location and pose from where the images are to be acquired. Then the appropriate pan and tilt angles can be determined with Viz by simulating the view of the selected camera.

3.3 Command Plan Generation

Once the sequence details had been worked out in this manner, the rover operations team generated the uplink sequence file using the "Virtual Dashboard" (see Fig. 3), a graphical user interface designed to control a robot in either a single-command tele-operational mode or a sequence generation mode. The rover operator uses a set of graphical tools to create commands to specific K9 subsystems; for example, mobility and cameras. The commands are written to an uplink file in the Contingent Rover Language (CRL)[3].

CRL is a flexible, conditional sequence language that allows for execution uncertainty. CRL expresses time constraints and state constraints on the plan, but allows flexibility in the precise time that actions must be executed. Constraints include conditions that must hold before, during, and after actions are executed. A feature of CRL is its support for contingent branches to handle potential problem points or opportunities in execution. CRL was designed to be a superset of existing sequence methods, such as time-stamped sequences or simple linear sequences of commands. In the field experiment, the command-generation tools generated a restricted subset of CRL that consisted of a linear list of commands to be executed sequentially.

3.4 Uplink/Downlink

Command sequence uplink and data downlink were accomplished through the use of ground-side software that was commanded through the Virtual Dashboard. The uplink software automatically compressed the uplink file, transported it to the rover and uncompressed it. The downlink software initiated remote routines that automatically packaged the data acquired during the previous sol, compressed it, moved it from the rover to the appropriate location in the file database, uncompressed and unpackaged it.

3.5 Plan Execution

The conditional executive (CX) is responsible for interpreting the CRL command plan coming from ground control, checking run-time resource requirements and availability, monitoring plan execution, and potentially selecting alternative plan branches if the situation changes. CX executes each step of the plan while verifying that the preconditions, maintenance conditions, and end conditions are respected. When there are branch points in the plan, CX chooses the option with the highest expected utility, computed over the remainder of the plan. When plan execution fails, CX reacts as specified within the plan, either failing a subpart (or all) of the plan, or attempting to continue on despite the failure. If the entire plan fails, CX puts the rover into a stable standby mode.

In the field experiment, because of the restricted subset of CRL used, CX acted much like a simple sequencer.

4 Sequence Example

To illustrate K9 rover operations during the field experiment, we will use two sequences from May 16, the third and final day of the joint test, seq-000516174053 (Sequence 1) and seq-000516185509 (Sequence 2). The purpose of Sequence 1 was to acquire a navigational panorama of the terrain in front of the rover. In Sequence 2, the K9 was to perform the following functions: image the mottled rock in front and to the left of the rover in stereo and color using the highest resolution available, drive closer to the target rock, image it once again, turn in preparation for traversing further down the arroyo, and acquire another navigational panorama.

In Sequence 1, the rover acquired an approximately 180-degree horizontal, 56-degree vertical, quarter-resolution monochrome stereo panorama and a front hazard camera stereo pair of images. Once the data was downlinked to the operations center at JPL, the stereo pipeline created a 3D model of the terrain in front of the rover. The terrain model and a model of the K9 rover were then loaded and displayed in Viz (see Fig. 2) and used to plan the first panorama of Sequence 2.

As seen in Fig. 4, the rover operator used Viz's simulation capabilities to ensure that the correct pan and tilt angles were chosen to include the target rock within the field of view of the high resolution camera. The user enters a pan and tilt angle for the simulated rover

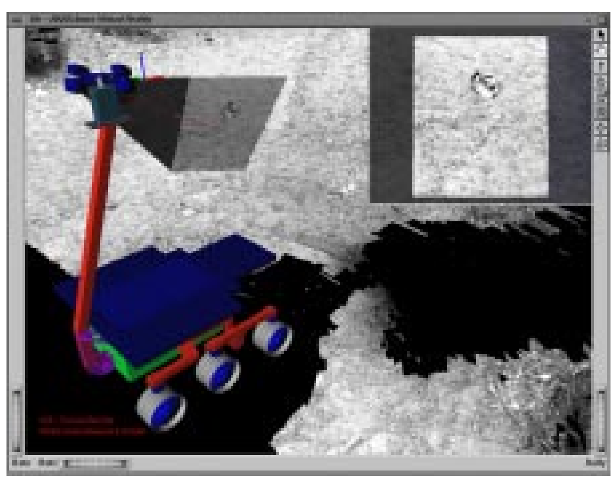

Figure 4: Planning the first panorama of target rock.

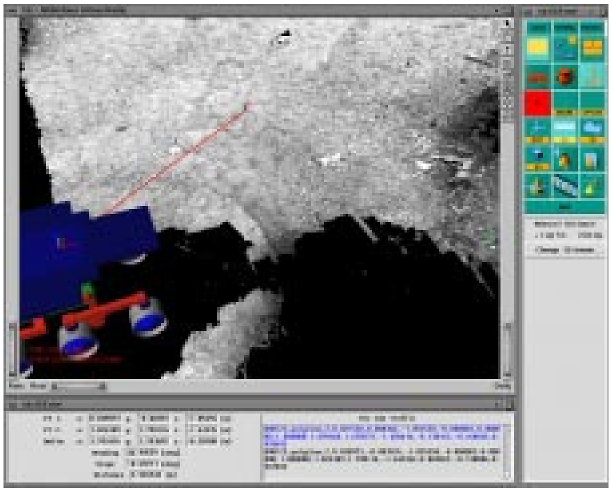

Figure 5: Planning the approach to the target rock.

within Viz and requests a simulation of the camera field-of-view and of the resulting image. Viz creates a cone showing where the field-of-view will intersect the terrain and a synthetic resulting image (shown in the upper right corner of Fig. 4).

The rover operator next planned the approach to the target rock by measuring the distance and bearing to the desired end position (see Fig. 5) using the distance tool within Viz. The VirtualRobot simulation moved K9 to the planned position within the virtual world. The rover operator could then check that the target rock was still within view of the mast cameras and not occluded by the solar panels (see Fig. 6). The ideal pan and tilt angles were then determined using the same method described above. In order to insure that the target would be imaged despite inaccuracies in the rover's traverse, a small panorama centered on the ideal pan/tilt coordinates was acquired. To calculate the extents of the panorama, the rover operator used the VirtualRobot to consider "what-if" scenarios. For instance, the operator could check to see where the rover would end up if it only completed 80% of it's commanded turn (not an unreasonable assumption). The operator could use the resulting rover position to determine a worst-case panorama extent.

Lastly, the rover operator planned the final turn of the sequence, which prepared the rover for its continued traverse down the arroyo. The final task of the sequence was to obtain a 180-degree horizontal, 56-degree vertical, quarter-resolution monochrome stereo panorama to be used for planning the next sequence (see Fig. 7).

In this manner, the rover operator worked with the Viz operator to create a written list of commands that

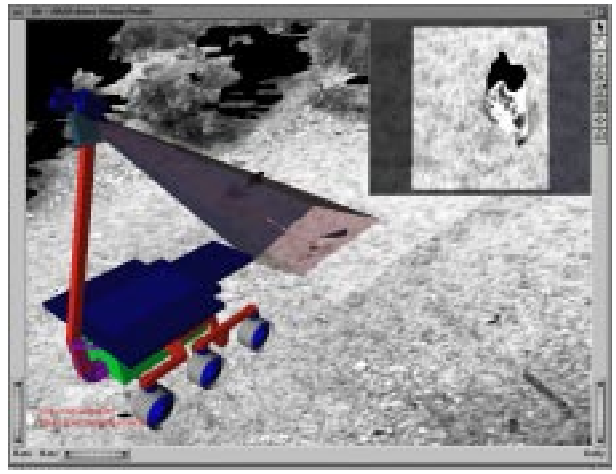

Figure 6: Planning the second panorama of target rock.

needed to be compiled into a CRL sequence using the Virtual Dashboard. The step-by-step generation of Sequence 2 using the dashboard is shown in Fig. 8. A panorama command is created using the field-of-view wedges in the Science Panel shown in yellow in the upper left panel. The user sets the extents of the panorama by dragging the endpoints of the wedges. The black lines within the wedges show an estimate of how many pan and tilt steps will be required for the given extents. Camera selection and resolution are set using the "Camera" and "Size" menus, respectively.

The rover operator generates drive commands using the Ackerman Steering Control Panel. As shown in the next two panels of Fig. 8, the operator enters point-turn or straight drive commands by dragging the yellow pointer in the desired direction. By pressing the "Trans/Rot" button, the user switches between the translation speed and total translation distance sliders and the rotation speed and total turn distance sliders.

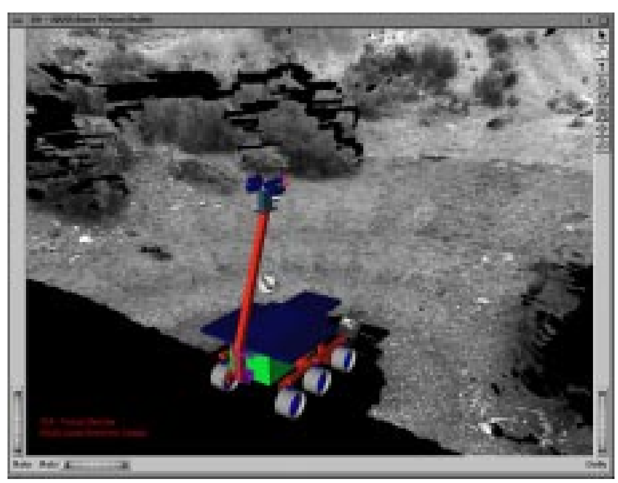

Figure 7: Model built from final navigational panorama of Sequence 2.

Once the rover operator has finished entering all the commands of the sequence, he selects "End CRL Sequence" from the "Seq" menu in the Telemetry Panel (see Fig. 3) then uplinks the sequence file to K9 again using the "Seq" menu. A sequence may be uplinked to the rover as one of two sequence types: Wait-type or Abort-type. When a Wait-type sequence file is uploaded, the onboard conditional executive will complete its current sequence before executing the new sequence. For an Abort-type sequence file, the CX will abort any sequence it is currently executing to immediately begin executing the new sequence. Fig. 9 shows the CRL sequence file for Sequence 2.

Upon completion of execution, the CX sends a message to the dashboard indicating success or failure. The rover operator then commands a data downlink using the "Downlink" command from the "Telemetry" menu of the Telemetry Panel.

The stereo pipeline again processed the downlinked data and the sequence generation process began again. Fig. 10 shows the resultant model of the second panorama of Sequence 2.

5 Field Experiment Results

The operations tools enabled a significant reduction in command sequence generation time, as compared to previous field experiments. During the three days of operations, we executed twelve command cycles and K9 traveled approximately sixty meters. K9 successfully fulfilled its scouting role by acquiring data for complete 3D models of three target rocks that the scientists selected as sampling candidates.

Viz was found to be very valuable for rover command planning. Predicted pointing of cameras following a move invariably captured the desired target. Although a range of pan and tilt extents was used to insure that the targets were captured, in most cases the image pointing for the target was quite close to where it had been predicted. Using Viz to estimate turn direction and drive distance led to significant improvement in the accuracy of placing the rover in the desired location as compared to previous tests. The total drive distance achieved (60m in 11 command cycles) was greater than had been achieved in previous experiments, although this may reflect the spacing of interesting science targets more than the efficiency of driving. Fig. 11 shows the total traverses for both the K9 and FIDO rovers during

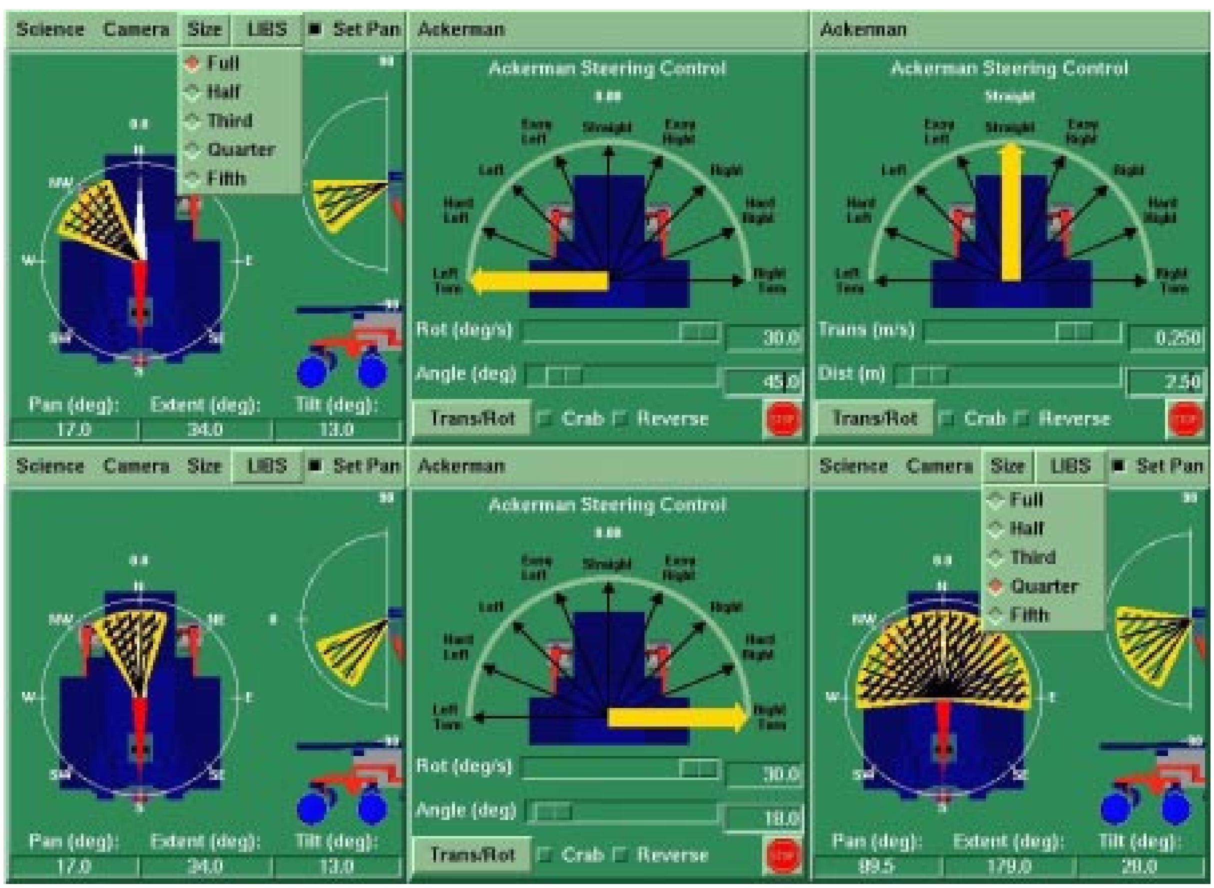

Figure 8: Generation of Sequence 2 using the Virtual Dashboard.

```
(block :id seq-000516185509
       :node-list (
   (task :id task-12
         :action icExposure
         :parameters (3 260) )
   (task :id task-1
         :action icMosaic
         :parameters (3 0 0 800 960 1 -1.127483 -
0.577704 -0.464258 -0.123918 0.166986 0.250568 0)
         :interrupt icAbort )
   (task :id task-2
         :action baseMove
         :parameters (1 0.000000 -1.000000 0.000000 -
0.523599 0.000000 0.845874 9999)
         :interrupt baseAbort )
   (task :id task-3
         :action baseMove
         :parameters (0 1.000000 0.000000 0.300000
0.000000 2.500000 0.845874 9999)
         :interrupt baseAbort )
   (task :id task-4
         :action icMosaic
         :parameters (3 0 0 800 960 1 -0.455531 -
0.940732 0.207694 -0.486947 0.166986 0.250568 0)
         :interrupt icAbort )
   (task :id task-5
         :action baseMove
         :parameters (1 0.000000 1.000000 0.000000
0.523599 2.500000 0.328925 9999)
         :interrupt baseAbort )
   (task :id task-6
         :action icPanTilt
         :parameters (-0.331613 -1.000074 0) )
   (task :id task-7
         :action icSnap
         :parameters (1 0 0 800 960 4 0)
         :interrupt icAbort )
   (task :id task-8
         :action icPanTilt
         :parameters (-0.038397 -0.977384 0) )
   (task :id task-9
         :action icSnap
         :parameters (3 0 0 800 960 4 0)
         :interrupt icAbort )
   (task :id task-10
         :action icPanTilt
         :parameters (0.254818 -0.965167 0) )
   (task :id task-11
         :action icSnap
         :parameters (0 0 0 800 960 4 0)
         :interrupt icAbort )
   (task :id task-12
         :action icExposure
         :parameters (23 90) )
   (task :id task-13
         :action icMosaic
         :parameters (23 0 0 800 960 4 -1.553343 -
0.977384 1.570796 0.000000 0.166986 0.250568 0)
         :interrupt icAbort )))
```

Figure 9: CRL file for Sequence 2.

the joint trial. In general, it takes longer to investigate science targets, particularly if *in situ* measurements are performed, than to drive between targets. This was illustrated by the fact that FIDO had only partially investigated one science target in 6 command cycles, while K9 had driven 15 m and obtained the full range of remote sensing observations of a target in 5 command cycles taking place during the same time period. This emphasizes the importance of making good use of the remote sensing capabilities onboard the rover to identify the most important targets to investigate with the more time consuming in situ observations.

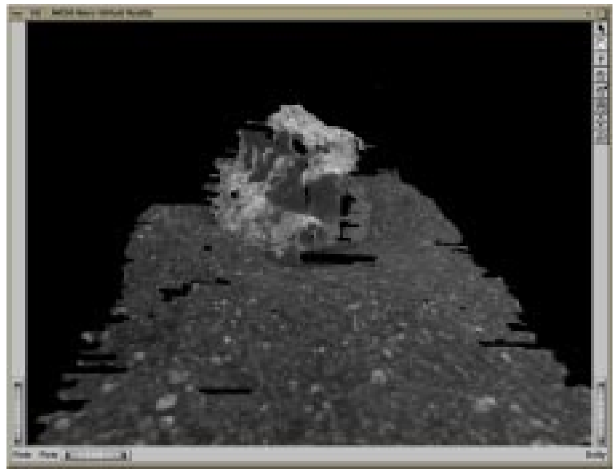

Figure 10: 3D model of target rock from second panorama of Sequence 2.

The Virtual Dashboard enabled the rover operator to quickly generate simple CRL sequence files, upload sequences and download the resulting data. Future improvements to the system will allow generation of conditional sequences.

The onboard conditional executive allowed remote, autonomous execution of command plans. When used with the full power of CRL, the CX creates a robust execution environment.

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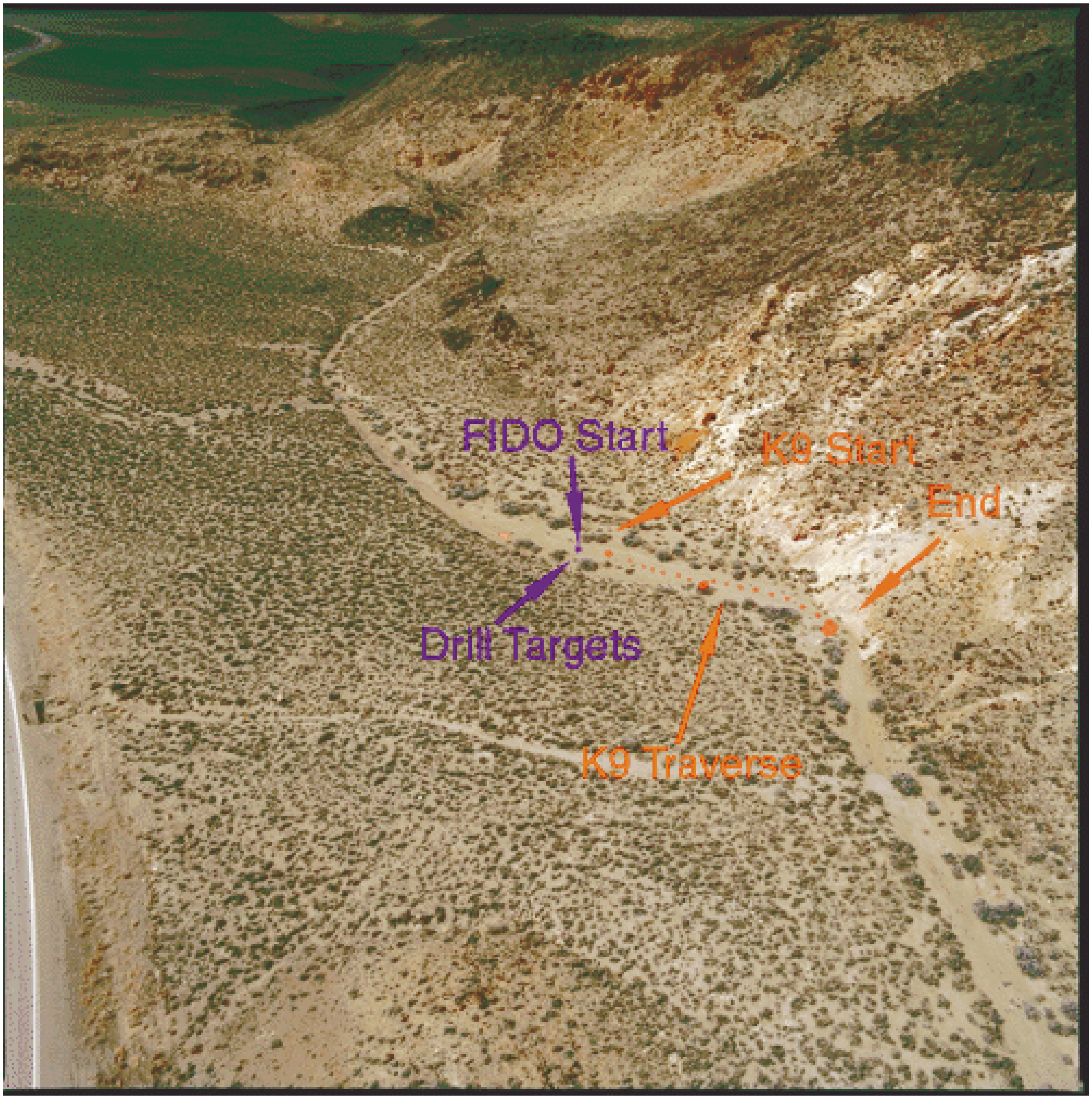

Figure 11: Total traverses of K9 and FIDO rovers during 3-day joint field experiment.

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